

The eclipsing binary TY CrA revisited: What near-IR light curves tell us ^{*}

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ABSTRACT

New photometric observations of the hierarchical eclipsing TY CrA system were taken in the optical with VYSOS6 and in the near-IR with SOFI and REMIR. They are the first observations showing the deep eclipse minimum of the pre-main sequence secondary in the near-IR. For the first time, the secondary minimum can be reliably used in the calculation of the O-C diagram of TY CrA. By now, the O-C diagram can be studied on a time basis of about two decades. We confirm, that the O-C diagram cannot be explained by the spectroscopic tertiary. For the first time, the light curve of the inner eclipsing binary is analysed in both optical and near-IR bands simultaneously. In combination with already published spectroscopic elements, precise absolute dimensions and masses of the primary and the secondary component are obtained using the ROCHE code. The inclusion of the near-IR data puts strong constraints on the third light which is composed of the reflection nebula, the spectroscopic tertiary and a visual fourth component. The absolute parameters of the inner eclipsing binary agree very well with previous work except of the primary radius ($1.46 \pm 0.15 R_{\odot}$) and luminosity ($40 \pm 10 L_{\odot}$) which are clearly smaller. While the parameters of the secondary are well understood when assuming an age of about 3–5 Myrs, the primary seems considerably undersized. Low metallicity cannot explain the parameters of the primary.

Key words: binaries: eclipsing – stars: pre-main sequence – stars: evolution – stars: fundamental parameters.

1 INTRODUCTION

The star-forming region R Coronae Australis (R CrA) harbors dozens of young intermediate- to low-mass stars (and brown dwarfs) of B8 to M8.5 spectral types. They have an age of between one and a few million years and

a distance of approximately 130 pc (for a review see Neuhauser & Forbrich 2008).

TY CrA is a hierarchical triple, maybe even quadruple system, embedded in a reflection nebula in the R Coronae Australis star forming region. The immediate environment of TY CrA has been studied recently in more detail by Geers et al. (2007), Juvela et al. (2008), Currie & Sicilia-Aguilar (2011), Sandell et al. (2011) and Kumar et al. (2011). Two components form a massive eclipsing double-lined spectroscopic binary (eSB2) with an orbital period of almost 3 days. While the primary, a B8 star with a mass of $3.16 M_{\odot}$, has already reached the main sequence, i.e. initiated stable hydrogen burning, the secondary still resides

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in the pre-main sequence (PMS) stage and has a mass of $1.64 M_{\odot}$ (Casey et al. 1998). A third spectroscopic component is in a wide orbit around the eclipsing pair (Casey et al. 1995; Corporon et al. 1996). A visual fourth component was detected by Chauvin et al. (2003).

The analysis of eSB2 allows us to derive the most fundamental parameters, mass and radius, as well as to obtain effective temperature and luminosity. Thus, the TY CrA eSB2 is one of the key objects that can provide precise constraints on the evolution of PMS stars.

The derivation of effective temperature is a particularly important issue. The analysis of the eclipse light curve (hereafter LC) yields the ratio of the effective temperatures of the two components but does not enable to determine individual temperatures. Temperatures for both components can be derived if a reasonable estimate is used for one of them. This step is a major problem in the analysis of PMS stars since their effective temperatures are not well-known a priori (Hillenbrand & White 2004; Ammler et al. 2005; Schöning & Ammler 2008). Because of a significant interstellar and circumstellar absorption towards TY CrA, observed colours have to be used with care (Casey et al. 1998).

TY CrA is one of only two known objects (see Hillenbrand & White 2004) which allow us to circumvent this problem: the primary has already reached the main sequence, so that its effective temperature can be estimated with a reasonable accuracy using the mass - temperature relation of main sequence stars. The secondary is still located in a PMS state.

The eclipsing nature of TY CrA was reliably established by Kardopolov et al. (1981) using *BV* photoelectric photometry. The authors observed ~ 0.4 mag deep minima consistent with an orbital period of 2.888777 days. Without spectroscopy it was, however, impossible to exclude the double orbital period for the system. The first spectroscopic orbit for TY CrA was obtained by Lagrange et al. (1993). The authors showed that the radial-velocity (hereafter RV) variations of all narrow spectral lines are periodic and consistent with the 2.888777 days period previously reported by Kardopolov et al. (1981). The width of lines, $v \sin i < 6 \text{ km s}^{-1}$, indicated subsynchronous rotation. The authors noticed the second system of much wider lines anticorrelating in RV with respect to the narrow lines. Corporon et al. (1994) confirmed that the broad lines correspond to the secondary component and derived orbits for both components. Later, Casey et al. (1995) found that TY CrA is a SB3 system. The RVs of the tertiary were found to correlate with the barycentric RV of the eclipsing pair confirming the gravitational bond. The authors were able to derive a precise solution of the circular orbit of the eclipsing binary after applying appropriate offsets to the primary and secondary data at different epochs. The measurements were insufficient to derive a unique solution of the tertiary orbit (also see Corporon et al. 1996) which most certainly has a long period compared to the orbit of the eclipsing binary.

Casey et al. (1998) obtained *wavy* photoelectric photometry of TY CrA (see also Vaz et al. 1998). The measurements used HD176423, HD176497 as comparisons. The authors confirmed the orbital period of the eclipsing binary of 2.89 days. The primary with spectral type B8 has a mass of $3.16 \pm 0.02 M_{\odot}$, the secondary $1.64 \pm 0.01 M_{\odot}$. Following Casey et al. (1998), the age of the eclipsing binary is of the

order of a few million years according to evolutionary models. The LC analysis was challenging mainly because of the very shallow secondary minimum in the optical bands with a depth of only ≈ 0.02 mag. The authors claim that the accuracy of the LC is not limited by observational errors, which are below 0.01 mag but by out-of-eclipse variability at a level of 0.05 mag (Vaz et al. 1998). The analysis is complicated by an offset of the 1992 data relative to the 1993 data around phase 0.6 which indicates another type of variation, possibly due to stellar spots. Casey et al. (1998) did not find a unique solution and pointed out the need for more photometric data. In addition, there are effects due to the spectroscopic tertiary (light-time effect), the third light detected in the LC analysis, the asymmetry of the primary minimum and the reflection nebula to be considered.

Observations of Chauvin et al. (2003) with VLT/NACO showed a visual companion to TY CrA separated by $0''.294$. If the additional component was a physical member of the system its spectral type would be M4. At such small separation the visual component contributes to all ground-based photometry and spectroscopy. Its light contribution in NIR is about 4% in the *J*, and 7.6% in the *K* passband, respectively. If physically bound, the fourth component would have significant consequences for the dynamical evolution of the system.

The aim of this work is to improve the knowledge on TY CrA and to solve open issues identified previously. Recent work shows that uncertainties can be substantially reduced when involving observations in the near-infrared. Covino et al. (2004) included near-infrared photometric data in the analysis of the young eclipsing binary RX J0529.4+0041 and were able to reduce the error bars on mass and radius of the components by $\approx 80\%$ compared to previous analyses in visual bands. The secondary minimum was deeper in the infrared band than in the optical thus allowing for higher accuracy. Also the determination of effective temperature from stellar colours benefits from the use of near-infrared observations, which are less affected by interstellar absorption. Schöning & Ammler (2008) found that calibrations based on an optical pass band and an infrared pass band (e.g., $(V - K)$) give effective temperature for young stars which agree best with spectral types.

The present work for the first time combines NIR light-curves (LCs) of TY CrA with observations in visual bands. The observational limitations encountered by Vaz et al. (1998) in the visual are overcome by using the advantages of wide-field imaging where lots of comparison stars are exposed simultaneously together with the target. The goal of the present paper is to conclusively determine the effective temperature of the pre-main sequence secondary and to solve uncertainties in previous LCs solutions.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Differential *JH* photometry

First *JHK_s* observations for this project were taken during two nights (July 30 and September 7) in 2006 with the SOFI instrument (see Moorwood et al. 1998, and Table 2) at the 3.5m ESO NTT at La Silla, Chile. The observations were scheduled to cover one secondary and one primary minimum of the system.

Table 1. Parameters of the variable and comparison stars used. The proper motions and $(B - V) = 0.85(B - V)_T$ colors were taken from the Tycho-2 Catalog (Høg et al. 2000). The distance to the system TY CrA was taken from Chauvin et al. (2003) and infrared colors, $(J - K)$, from 2MASS (Skrutskie et al. 2006); cmp5 = 2MASS 19013729-3649210 = USNOB1 0531.0836104.

Comp.	GSC	HD	SAO	μ_α [mas.y ⁻¹]	μ_δ [mas.y ⁻¹]	d [pc]	$(B - V)$	$(J - K)$	sp. type
TY CrA	7421-1126	—	210829	-0.2(1.3)	-28.6(1.2)	136 ⁺²⁵ ₋₁₉	0.463(32)	0.813(23)	B8e
cmp1	7421-1061	176423	210834	6.1(1.4)	-27.3(1.4)	—	0.291(20)	0.240(23)	A1III/IV
cmp3	7421-1163	176497	210840	3.3(1.3)	-28.5(1.3)	—	0.170(10)	0.080(28)	A0IV
cmp5	—	—	—	—	—	—	—	1.939(33)	—

Table 2. Overview of telescopes/instruments and detectors used to obtain photometry of TY CrA. Abbreviations of the observatories (Obs.): LS – La Silla (29°15′0 S, 70°44′0 W); CA – Cerro Armazones (24°36′0 S, 70°11′0 W); CT – Cerro Tololo (30°10′0 S, 70°48′0 W).

Obs.	Telescope/Instrument	Aperture [cm]	Filters	Detector	Size [pix]	FoV
LS	NTT/SOFI	358	JHK_S	Hawaii HgCdTe	1K×1K	4′66 × 4′66
	REM/REMIR	60	JHK_S	Hawaii I	0.5K×0.5K	10′0 × 10′0
	REM/ROSS	60	VRI	Apogee Alta	1K×1K	10′0 × 10′0
CA	VYSOS6	15	$BVRI$	Apogee Alta U16M	4K×4K	2°42′0 × 2°42′0
CT	1.3m/ANDICAM	130	$BVRI$	Fairchild 447	2K×2K	6′0 × 6′0
		130	$YJHK$	Hawaii HgCdTe	1K×1K	2′4 × 2′4

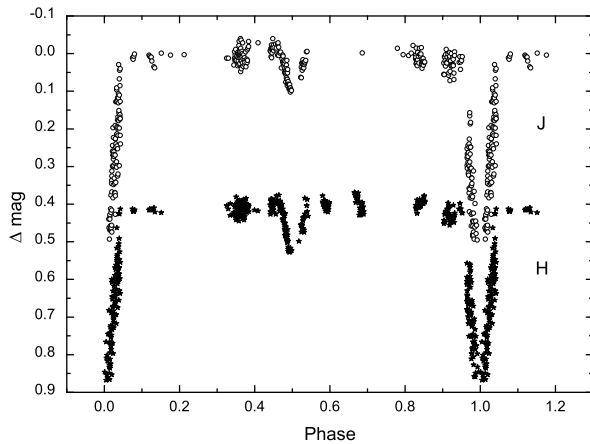


Figure 1. The JH LC of TY CrA obtained by us with REMIR (2009 and 2011) and SOFI (2006) at La Silla. The LC is incomplete because of bad weather and pointing problem. The primary minimum was obtained with SOFI in 2006 and the rest of LC was observed with REMIR in 2009 and 2011. The observations from 2011 were reduced with respect to HD 176423. For other observations we used cmp5 as the comparison star (see Table 1). Therefore, to obtain whole LC we took into account the brightness difference of the comparison stars (see the text). Note that the errors of LC points in JH photometry are within the range of 0.003 – 0.010 mag.

The observations during the first night suffered from strongly variable conditions and were not used in the analysis. The primary minimum observed in the second night is of good quality. In addition to precise minima timing (see Section 3), the data were used for the LC analysis. All SOFI observations use cmp5 as the comparison star (see Table 1 and Figure 2)

Additional infrared photometry was taken in 2009-2011 with REM¹ (Rapid Eye Mount, Zerbi et al. 2001; Antonelli et al. 2003; Zerbi et al. 2004) (60cm diameter rapid response telescope) operated at La Silla, Chile. The telescope hosts two instruments: REMIR, an infrared imaging camera, and ROSS, a visible light imager. The two cameras can observe simultaneously thanks to a dichroic plate placed before the telescope focus.

In order to fully cover the NIR JHK_s LC we got REM observing time by three proposals (in the periods AOT19, AOT21 and AOT23). The observations strongly suffered from bad weather and technical problems. The observing programme has been completed to a low percentage even though additional DDT time was granted. The first observations taken in AOT19 and 21 followed the standard approach of differential photometry, i.e. a pre-defined field is observed containing the target and the selected comparison star (cmp5) (see Figure 2). However, the REM frames are affected by pointing and off-centering problems, so that comparison star and sometimes also the target were off the frames. The 2010 data (AOT21) are of low quality and were excluded from the LC analysis. For period AOT23, we followed a different observing strategy. Since the pointing was not sufficiently precise, we decided to observe other fields including comparison stars already used by Casey et al. (1998) and Vaz et al. (1998), and to center the pointing at these stars (HD 176423 (cmp1) and HD 176497 (cmp3)). These fields and TY CrA were observed in an alternating sequence with high frequency which must not be lower than the frequency of variations of the near-infrared background. The observational strategy was further improved by observing selected critical phases (ingress, egress, minimum) of many

¹ <http://www.rem.inaf.it/>

eclipses distributed over different nights instead of observing only a few eclipses continuously from ingress to egress. This way, the loss of a single night due to weather or technical problems had less effect on the overall success of the observations. Eventually, we obtained 2 secondary minima and out-of-eclipse observations around phases 0.25 and 0.75.

The same observing strategy was used also in additional near-IR photometry carried out by ANDICAM. This is a simultaneous optical and NIR imaging instrument (DePoy et al. 2003) operated by the SMARTS consortium at the 1.3m CTIO telescope, Chile. The field of view of the NIR camera is roughly centered on the larger field of view of the optical arm. We observed in two nights in May 2011; however, because of bad observing conditions (we obtained only several usable datapoints), this observation was excluded from the following analysis.

Concerning comparison stars, note that, in the case of SOFI data (2006) and REM data from 2009, we used 2MASS 19013729-3649210 (RA₂₀₀₀: 19:01:37.292, DEC₂₀₀₀: -36:49:21.04) as additional comparison star. The REM observations in 2011 were measured with respect to HD 176423. The additional standard is fainter than HD 176423 in the *J* and *H* bands, by 1.799 ± 0.006 and 0.642 ± 0.004 respectively. The *K_S* band observations, especially in the case of REM, were very scattered. Hence, for the photometric analysis we could use only the *JH* LCs.

The near-IR *JH* data reduction was implemented using IDL², ESO MIDAS³, and ESO ECLIPSE⁴. The flat-field frames and the bad pixel masks were created using the ESO ECLIPSE *flat* and *average* recipes. The flat-field division, bad pixel correction, sky subtraction, and shift and add of the science frames was performed using the ESO ECLIPSE *jitter* recipe.⁵

In further reduction tasks, the IRAF package⁶ has been used. In the next step the astrometric solution of the frames was performed. The WCS system was determined using the 2MASS on-line catalogue for reference⁷. Then the aperture photometry of the target and comparison stars has been done. The instrumental magnitudes for several apertures appropriate for the seeing conditions at site were determined. The details of all near-IR observations are mentioned in the journal of observations in the Table 3. The differential extinction was neglected.

Note that the errors of the LC data points in *JH* photometry are between 0.003 and 0.010 mag. In contrast to the optical images, there is no contamination due to the reflection nebula. Figure 2 shows that in the near-IR there is no background emission from the nebula, contrarily to the optical where a strong contribution from the reflection nebula is observed.

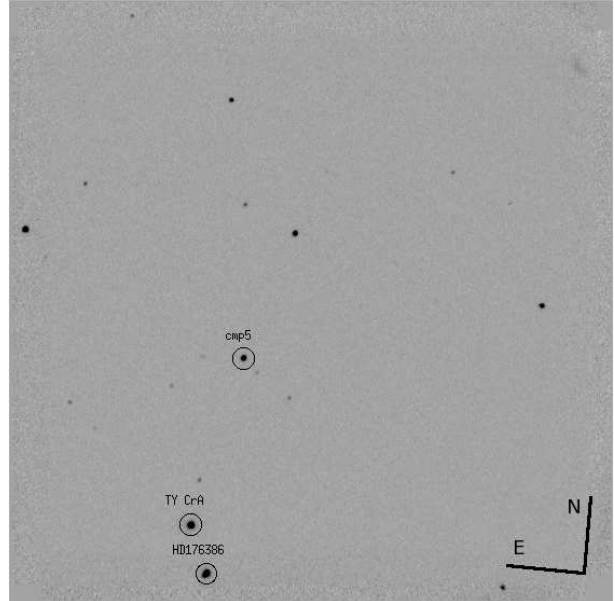


Figure 2. The field around TY CrA in the H passband (the image taken on June 27, 2009).

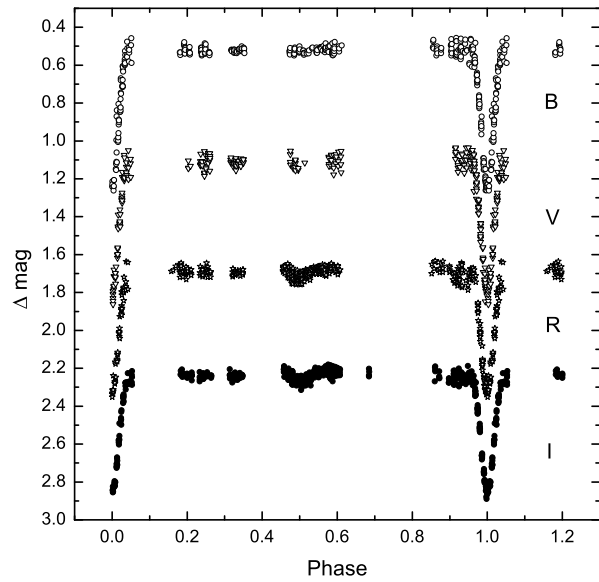


Figure 3. The *BVRI* LC obtained by us with VYSOS6 at the Cerro Armazones in 2009. The errors of individual points in the *BVRI* LCs are in the range of 0.006–0.009 mag. The LCs were arbitrarily shifted in magnitudes for clarity.

Interestingly, we noticed an asymmetry in the primary minimum in the near-IR SOFI data which was already noticed by Casey et al. (1998) in the optical.

2.2 *BVRI* CCD photometry

The optical CCD photometry of TY CrA was performed by VYSOS6, a wide field imaging instrument located at Cerro Armazones Observatory, Chile (Haas et al. 2011).

Observations of TY CrA were taken in 2009 and 2011 (Fig. 3). By the second campaign in 2011, VYSOS6 got an

² <http://idlastro.gsfc.nasa.gov/contents.html>

³ <http://www.eso.org/sci/software/esomidas/>

⁴ <http://www.eso.org/sci/software/eclipse/>

⁵ Each REMIR jitter sequence consists of five frames. The jitter pattern has a pentagon shape and is exactly the same for each sequence but might be rotated. Mostly, the offsets were made available to the recipe beforehand and refined by cross-correlation search when possible. In many cases, however, the *jitter* recipe even succeeded in performing a blind offset search.

⁶ <http://iraf.noao.edu/>

⁷ <http://www.ipac.caltech.edu/2mass/releases/allsky/>

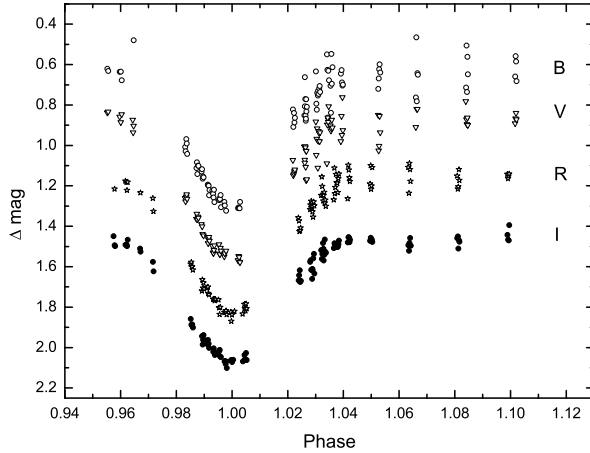


Figure 4. Primary minimum in *BVRI* obtained with VYSOS6 at the Cerro Armazones observatory in 2011.

identical twin installed on the same mount. One telescope offers the filter combination *VR* and the other *BI*, so that observations are taken in two filters simultaneously. Both telescopes are equipped with an Apogee Alta U16M 4096×4096 pixels CCD camera each, providing a $2^{\circ}42'0 \times 2^{\circ}42'0$ field of view. During the first observing campaign we have covered the whole LC in *BVRI*, used for the analysis described in the following. Unfortunately, in the case of the 2011 photometry, we obtained only an incomplete primary minimum (see Fig. 4). The secondary minimum was not observed at all because of bad weather.

For the optical differential photometry, we also used HD 176423 and HD 176497 as comparison and check star, respectively. The stars were found to be constant within the observational accuracy throughout the observing period. We reduced all optical data in a standard manner (bias, dark, flat-field corrections), and aperture photometry was performed using IRAF and custom written tools.

The LCs obtained in 2009 with VYSOS6 show that the depth of the secondary minimum (at phase 0.5) increases towards the redder bands (*R*, *I*) and reaches almost 0.10 mag in the *I*-band. The errors of individual points in the *BVRI* LCs are in the range of 0.006–0.009 mag.

The visual LCs of TY CrA are contaminated by the reflection nebula. Part of its light is subtracted as background within the aperture photometry. Any remaining contribution is corrected for by fitting the third light in the LC analysis.

3 MINIMA DETERMINATION AND THE LIGHT-TIME EFFECT

Our observations enabled us to determine 3 minima times of the TY CrA eclipsing pair⁸, which add to the Casey et al. (1998) data and one recent observation by Paschke (2010). They are listed in Tab. 4. The times of minima were determined separately for all filters using the Kwee & van Woerden (1956) method and then the weighted averages were calculated.

⁸ Partially covered eclipses were not used for the timing.

Table 3. The journal of CCD (*BVRIJH*) observations of TY CrA obtained at La Silla (REMIR, SOFI) and Cerro Armazones (VYSOS6) observatories in the period 2006 – 2011. The julian date HJD_{mean} is corresponding to the beginning of observation. $N_{im.}$ – number of CCD frames in *R* and *J* filter.

Date	HJD_{mean} 2 400 000+	Phase	Filter	$N_{im.}$
VYSOS6				
Jun 26, 09	55009.719	0.184 – 0.211	<i>BVRI</i>	24
Jun 27, 09	55010.565	0.476 – 0.593	<i>BVRI</i>	84
Jun 28, 09	55011.786	0.899 – 0.933	<i>BVRI</i>	25
Jul 22, 09	55035.644	0.158 – 0.181	<i>BVRI</i>	8
Jul 23, 09	55036.505	0.456 – 0.565	<i>BVRI</i>	98
Jul 24, 09	55037.648	0.852 – 0.882	<i>BVRI</i>	20
Aug 26, 09	55070.530	0.234 – 0.263	<i>BVRI</i>	23
Aug 27, 09	55071.518	0.576 – 0.609	<i>BVRI</i>	17
Aug 28, 09	55072.492	0.914 – 0.993	<i>BVRI</i>	44
Aug 31, 09	55075.494	0.953 – 0.031	<i>BVRI</i>	59
Sep 01, 09	55076.559	0.321 – 0.349	<i>BVRI</i>	25
Sep 02, 09	55078.496	0.992 – 0.048	<i>BVRI</i>	41
May 27, 11	55709.812	0.699 – 0.711	<i>BVRI</i>	20
May 29, 11	55711.851	0.406 – 0.420	<i>BVRI</i>	20
May 30, 11	55712.674	0.690 – 0.703	<i>BVRI</i>	19
Jun 04, 11	55717.879	0.492 – 0.506	<i>BVRI</i>	20
Jun 06, 11	55719.707	0.125 – 0.172	<i>BVRI</i>	27
Jun 08, 11	55721.826	0.858 – 0.874	<i>BVRI</i>	21
Jun 09, 11	55722.674	0.152 – 0.209	<i>BVRI</i>	40
Jun 10, 11	55723.681	0.501 – 0.514	<i>BVRI</i>	21
Jun 11, 11	55724.809	0.891 – 0.906	<i>BVRI</i>	20
Jun 12, 11	55725.893	0.191 – 0.266	<i>BVRI</i>	29
REM-IR				
Apr 02, 09	54923.907	0.478 – 0.481	<i>JH</i>	5
Jun 13, 09	54995.740	0.344 – 0.368	<i>JH</i>	29
Jul 23, 09	55036.469	0.443 – 0.456	<i>JH</i>	12
Jul 24, 09	55036.509	0.457 – 0.489	<i>JH</i>	39
Jul 25, 09	55037.801	0.344 – 0.368	<i>JH</i>	29
Aug 20, 09	55063.585	0.830 – 0.852	<i>JH</i>	28
Sep 05, 09	55079.567	0.363 – 0.384	<i>JH</i>	24
Jun 12, 09	55359.749	0.352 – 0.380	<i>JH</i>	24
Jun 22, 09	55369.732	0.808 – 0.832	<i>JH</i>	21
Apr 25, 11	55676.713	0.074 – 0.126	<i>JH</i>	9
May 01, 11	55682.712	0.150 – 0.494	<i>JH</i>	6
Jun 23, 11	55735.680	0.486 – 0.539	<i>JH</i>	12
Aug 14, 11	55787.552	0.442 – 0.527	<i>JH</i>	4
SOFI				
Sep 07, 06	53986.460	0.964 – 0.042	<i>JH</i>	242

For computation of minima times we have used only data in the phase interval ± 0.05 around either of the minima. This approach minimizes the influence of the minima asymmetries (van't Veer 1973).

Figure 5 shows the (O-C) residuals for all available minima (Table 4) with respect to the optimum ephemeris determined by the LC modeling (Table 5). As expected, for a detached binary, the orbital period of the system is stable. Nevertheless, the (O-C) residuals exhibit deviations significantly larger than their standard errors. Corporon et al. (1996) presented five different spectroscopic orbital solutions

Table 4. Primary and secondary minima times of TY CrA. For some minima, the filters used were not given in the original publication (Casey et al. 1998). For new minima observed in more than one filter the weighted average is given.

HJD	σ	Filter	Type
2 400 000+	[days]		
Casey et al. (1998)			
47694.7971	0.0009	—	pri
47700.5740	0.0005	—	pri
47710.68	0.08	—	sec
48783.8703	0.0013	—	pri
49153.6302	0.0032	<i>y</i>	pri
49160.85	0.02	<i>y</i>	sec
49163.74	0.01	<i>y</i> <i>b</i>	sec
49514.7310	0.0003	—	pri
49527.738	0.005	—	sec
49537.8414	0.0008	—	pri
49543.6193	0.0003	—	pri
This work			
53986.55284	0.00038	<i>JH</i>	pri
55036.64046	0.00035	<i>IR</i>	sec
55075.63231	0.00016	<i>BVRI</i>	pri
Paschke (2010)			
55387.619	0.005	<i>V</i>	pri

for periods of the outer orbit $P_3 = 126$ -270 days. The most probable are their solutions #1 ($P_3 = 270$ days) and #2 ($P_3 = 268$ days). The expected light-time effect (hereafter LITE) amplitude modulating the binary eclipse timings was computed for solution #1 and the following masses of the components: $M_1 = 3 M_\odot$, $M_2 = 1.6 M_\odot$ and $M_3 = 1.2 M_\odot$. Using the published major axis $a = 1.47$ a.u., the outer orbit inclination $i = 20^\circ$, and the above masses we get the projected semi-major axis of the eclipsing pair as: $a_{12} \sin i = 0.104$ a.u. corresponding to 51.9 light seconds (or 0.0006 days). In the view of the most precise minima having $\sigma = 0.0002$ days and probable systematic errors (caused e.g. by activity of TY CrA), the detection and useful analysis of the timing signal caused by the third component can hardly be performed using the ground-based photometry.

Because of the short period of the outer orbital pair the RV observations are more sensitive and useful in the decisive determination of the orbital elements. To summarize, we agree with Casey et al. (1998) in that the photometric O-C diagram of the inner eclipsing binary cannot be explained by orbital solutions for the spectroscopic tertiary suggested previously by Corporon et al. (1996).

4 LIGHT CURVE ANALYSIS

Unfortunately, optical (*BVRI*) data and near-IR (*JH*) photometry were obtained in different time intervals (see Table 3). Most of the optical photometry was taken in 2009, while the near infrared data used for analysis in 2006, 2009, and 2011. Because of the extreme stability of LCs, we attempted to model all photometric data simultaneously. Separate solutions of visual and NIR data were also performed.

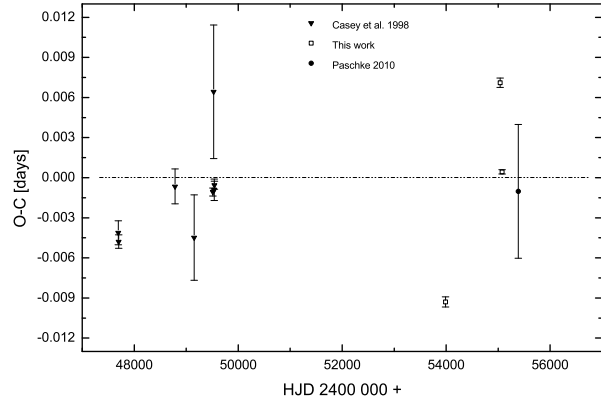


Figure 5. (O-C) diagram for all published and new minima (obtained from optical and NIR LCs) timings corresponding to the optimal ephemeris obtained by the simultaneous multi-colour LC analysis (Table 5).

Our photometry of TY CrA is the sum of the eclipse LC of the inner binary and a constant light contribution of the unresolved third component and the visual companion (0.3 arcsec from the unresolved triple). Moreover, TY CrA and HD 176386 (1'1 southwest of TY CrA) illuminate the reflection nebula NGC 6726/6727, whose light is a significant contributor to the observed flux (Casey et al. 1998). The light from the two stars in the eclipsing pair is of principal interest here. The remaining sources produce a constant offset, so-called third light, decreasing the LC amplitude and complicating the analysis. Because of the three different sources, the third light cannot be modeled as a single stellar source (defined by its fractional radius, and effective temperature). Hence the third light will be treated without any assumptions and independently in the individual passbands.

The latest version of the code *ROCHE* was employed (Pribulla 2012). The LC of the system was modeled assuming (1) radiative envelopes with bolometric albedos $A_1 = A_2 = 1.00$ (e.g. Rucinski 1969) and gravity darkening coefficients $g_1 = g_2 = 1.00$ appropriate for the B8V spectral type (see Pantazis & Niarchos 1998), (2) limb darkening coefficients automatically interpolated from extensive tables of van Hamme (1993) for average surface gravity $\log g$, average T_{eff} and given passband, (3) solid body rotation of the components (no differential rotation), (4) synchronous rotation of the secondary component $F_2 = 1$ and no rotation of the primary $F_1 = 0$ (see below), (5) rotational axes perpendicular to the orbital plane, (6) circular orbit, (7) no photospheric spot(s), and (8) local intensity computed using model atmospheres (local $\log g$, T_{eff} , and λ) for the solar chemical composition. The mutual irradiation effects were approximated by single reflection. Surface grids were derived from a icosahedron in such a way that surface elements are close to equilateral triangles of similar size.

In the optimization process the following parameters were adjusted: T_0, P - corresponding to the primary minimum and orbital period, i - inclination angle, Ω_1, Ω_2 - generalized surface equipotentials, T_2 mean temperature of the less massive and colder secondary component, $l_1(\lambda) + l_2(\lambda)$ - passband-specific unit-less normalization factors,

and $l_3(\lambda)$ - third light⁹. The temperature of the primary $T_1 = 12000 \pm 500$ K was adopted from Casey et al. (1998) while the spectroscopic orbit ($K_1 = 85.2 \pm 0.2$ km.s⁻¹, $K_2 = 164.6 \pm 1.6$ km.s⁻¹) was adopted (not adjusted) from Casey et al. (1995).

Before arriving at the final solution we extensively tested the subsynchronous rotation hypothesis. Because of the small fractional radius¹⁰ of the primary component ($r_2 \sim 0.1$) the asynchronism has a very small effect on the LC shape. The relative change of the equatorial radius of the primary component between the case of no rotation ($F_1 = 0$) and synchronous rotation ($F_1 = 1$) is about 0.8% only. Hence we assume that the primary does not rotate at all. The multi-colour LCs were solved by the method of differential corrections. The optimisation process always resulted in the same parameter set (we used different starting parameters) indicating uniqueness of the solution.

The derived photometric elements are presented in Table 5. The values found for l_3 are 0.8965, 0.6969, 0.6791, 0.6940, 0.3032, and 0.4205 for B , V , R , I , J and H , respectively, showing the increasing influence of the nebular contribution for shorter wavelength (see Table 5), the additional stellar component(s) dominating in the NIR. The best fit to the $BVRIJH$ LCs is displayed in Fig. 6. In the case of the H -band data the primary minimum together with fit has lower (~ 0.08 mag) amplitude than in the other filters. This fact is due to the bad data quality in the primary minimum. The scattered points have been removed so that the amplitude of the fit is lower and the third light contribution is larger. The $BVRIJH$ LCs solution for synchronous rotation and rotational axes perpendicular to the orbital plane predicts $v_1 \sin i = 25.4$ km s⁻¹ and $v_2 \sin i = 40.0$ km s⁻¹.

The absolute parameters of the primary and secondary components of TY CrA (corresponding to the simultaneous fit to the $(BVRIJH)$ LCs) are given in Table 6. The values of most parameters, except of R_1 and L_1 , are consistent with those derived by Casey et al. (1998). We obtained about 19% smaller diameter of primary and about 10% larger diameter of the secondary component compared to values given by Casey et al. (1998). Such a difference in diameter translates to even larger difference in luminosity: our value for the primary is by 42% lower. This discrepancy will be discussed in the following section.

To better compare our results and those of Casey et al. (1998), we also performed an analysis of the optical $BVRI$ LCs only. The resulting parameters given in Table 6 are still not consistent with those presented by Casey et al. (1998): R_1 and L_1 are about 15% and 35% smaller, respectively.

In addition, we solved the LCs in the $BVRI$ passbands without third light reproducing very closely the parameters given by Casey et al. (1998). However a good solution in the J and H bands cannot be achieved without admitting a third light contribution. The conclusion is that the near-IR data allows us to constrain the third light very well.

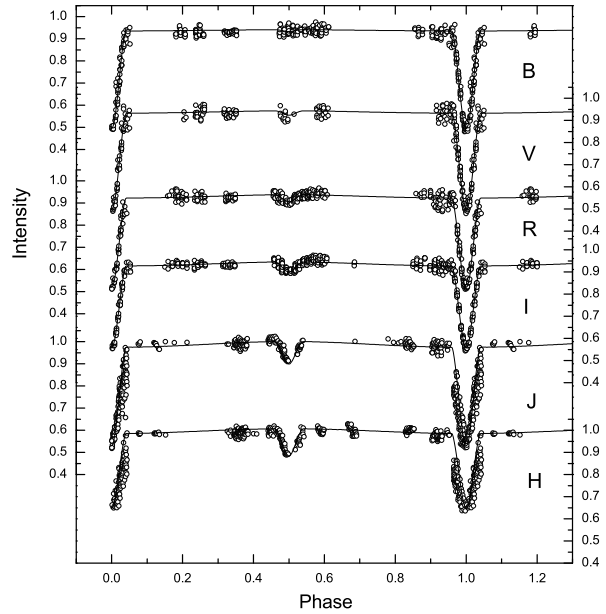


Figure 6. Best fits to the observed $BVRIJH$ LCs of TY CrA resulting from the simultaneous modeling of all bands. The orbital phases are determined according to the new ephemeris given in Table 5.

5 THE EVOLUTIONARY STATE OF TY CRA

5.1 Mass-radius diagram

Masses and radii are the most fundamental parameters derived from the observations. They are hardly affected by uncertainties in the adopted effective temperature of the primary component. We varied the primary temperature in the light curve analysis from 10,000 K to 14,000 K in order to see whether there is any effect on the resulting masses and radii. While luminosity varies drastically from 30 to more than $70 L_\odot$, the changes in masses and radii remain well below the formal error bars. In other words, the derived values of mass and radius are very robust w.r.t. an uncertain primary T_{eff} .

The radii are indicative of the evolutionary state of both components. The mass-radius diagram in Fig. 7 compares the loci of both components to previous assessments by Casey et al. (1998) and precise data of other binaries (Torres et al. 2010). In addition, PISA isochrones of Tognelli et al. (2011) of different age and metallicity are overplotted. Casey et al. (1998) have already noticed that TY CrA has reached the main sequence while the secondary still resides in the pre-main sequence phase.

Not only the secondary but also the primary is an important object since it is located in an otherwise empty region of the mass-radius diagram at small radii. Our value of the primary radius is even lower than the value given by Casey et al. (1998). The comparison to the Torres et al. (2010) data shows that the primary component seems considerably undersized. The primary only agrees with the models when adopting a metallicity of $Z=0.003$ or less (Figs. 7b and 7c). For comparison, Fig. 7a shows the $Z=0.0125$ isochrone according to the metallicity adopted by Gennaro et al. (2012). Casey et al. (1998) compared to models at even higher metallicity, Sun-like and Hyades-like.

⁹ The third light is expressed in ROCHE as $l_3 = L_3/(L_1 + L_2)$.

¹⁰ relative to the major axis a , unitless quantity

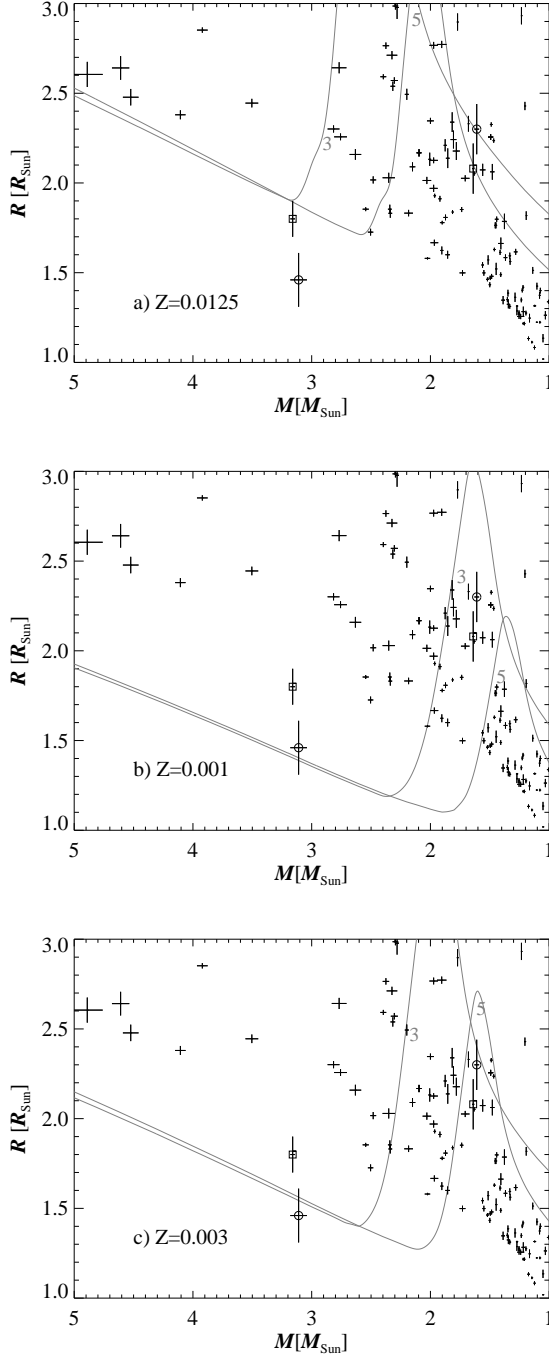


Figure 7. Mass-radius diagram. The new measurements of TY CrA (circles) are compared to the previous results obtained by Casey et al. (1998, squares) and the data of other binaries compiled by Torres et al. (2010). The measurements are compared to theoretical isochrones for 3 and 5 Myrs from Tognelli et al. (2011) at different metallicity: **a)** $Z=0.0125$, $Y=0.255$, $X_D = 2 \cdot 10^{-5}$, $\alpha = 1.20$; **b)** $Z=0.001$, $Y=0.232$, $X_D = 4 \cdot 10^{-5}$, $\alpha = 1.20$; **c)** $Z=0.003$, $Y=0.236$, $X_D = 4 \cdot 10^{-5}$, $\alpha = 1.20$.

Table 5. Photometric elements (coming from *BVRI* and *JH* simultaneous analysis) of the eclipsing pair in the TY CrA system and their standard errors, σ (number in parentheses gives the error of the last digit) – i – inclination; e – eccentricity; $q = m_2/m_1$ – mass ratio and $K_1 + K_2$ – sum of radial-velocity semi-amplitudes (adopted from Casey et al. 1995); $\Omega_{1,2}$ – generalized surface potentials; $f_{1,2}$ – asynchronous rotation factors, T_2 – effective temperature of the secondary component; r_{pri} , r_{sec} – volume mean fractional radii; $L_1^B/(L_1^B + L_2^B)$ – monochromatic lights and l_3 – contribution of the third light. Parameters fixed (not adjusted) in the solution are denoted by a superscript “ f ”. The uncertainty of the secondary-component temperature contains quadratically added 200 K error resulting from the 500 K error of the primary-component temperature estimated by Casey et al. (1998). The error has not been propagated to uncertainties of passband-specific relative lights $L_1/(L_1 + L_2)$.

Parameter	TY CrA
HJD ₀	2 449 537.8423(25)
P [days]	2.88877912(21)
i [°]	85.1(10)
e	0 ^f
Ω_1	10.4(10)
Ω_2	4.5(6)
F_1	0.0 ^f
F_2	1.0 ^f
q	0.518 ^f
$K_1 + K_2$ [km.s ⁻¹]	249.8 ^f
T_1 [K]	12000 ^f
T_2 [K]	4900(250)
r_{pri}	0.102(10)
r_{sec}	0.161(9)
$L_1^B/(L_1^B + L_2^B)$	0.9674(14)
$L_1^V/(L_1^V + L_2^V)$	0.9177(32)
$L_1^R/(L_1^R + L_2^R)$	0.8581(10)
$L_1^I/(L_1^I + L_2^I)$	0.7905(9)
$L_1^J/(L_1^J + L_2^J)$	0.6592(13)
$L_1^H/(L_1^H + L_2^H)$	0.5400(11)
l_3^B	0.8965
l_3^V	0.6969
l_3^R	0.6791
l_3^I	0.6940
l_3^J	0.3032
l_3^H	0.4205

The secondary agrees with a very young age of some 3-5 Myrs for any set of isochrones, in accordance with previous estimates by Casey et al. (1998, ≈ 3 Myrs) and Gennaro et al. (2012, $\approx 4 - 5$ Myrs).

5.2 HR diagram

The evolution of the radiative quantities luminosity and effective temperature is studied in the HR diagram (Fig. 8). Again, the new measurements are compared to the previous location in the HR diagram according to Casey et al. (1998) and to PISA models, now including stellar tracks. For clarity and since we do not gain additional insight, the Torres et al. (2010) data is not shown in Fig. 8.

Figure 8a aims at reproducing fig. 8 of Gennaro et al. (2012) who fitted the location in the HR diagram based on the Casey et al. (1998) data. However, Fig. 8a looks more

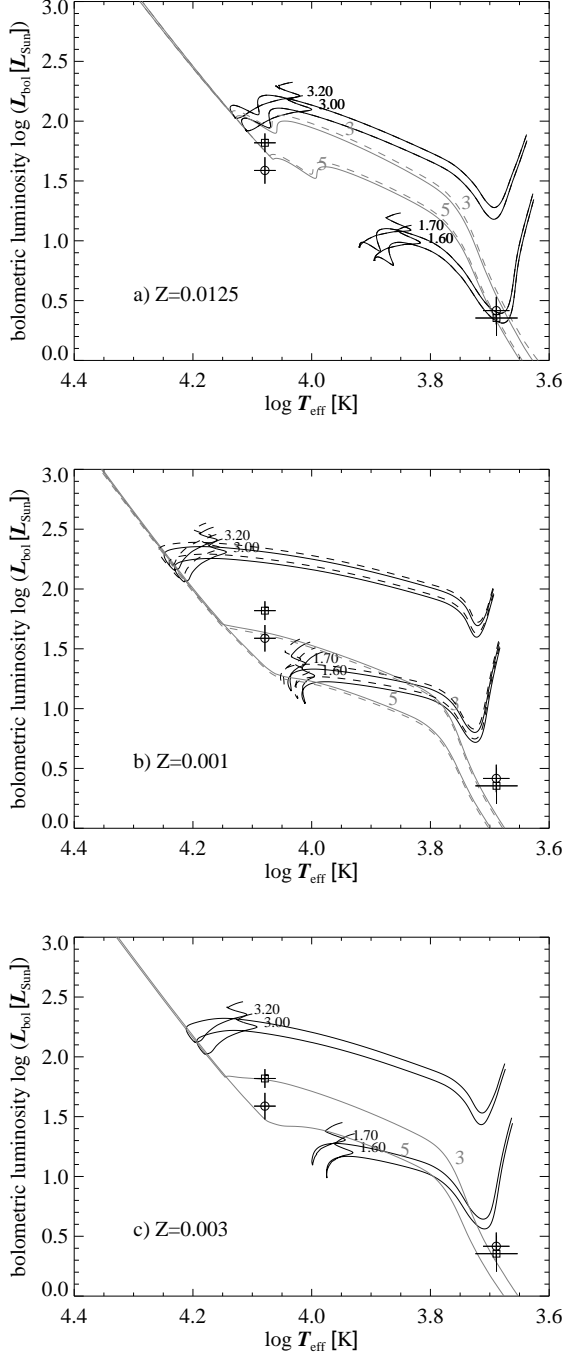


Figure 8. HR diagram. The new measurements of TY CrA (circles) are compared to the previous results obtained by Casey et al. (1998, squares). The measurements are compared to PISA models (Tognelli et al. 2011) at different metallicity. Theoretical isochrones for 3 Myr and 5 Myr are displayed as well as mass tracks for 1.6, 1.7, 3.0, and 3.2 M_{\odot} : **a)** $Z=0.0125$, $Y=0.255$, $X_D = 2 \cdot 10^{-5}$ (solid)/ $4 \cdot 10^{-5}$ (dashed), $\alpha = 1.20$ (sets with different X_D are used to enable comparison with Gennaro et al. (2012), and to show that different X_D has relatively small effect); **b)** $Z=0.001$, $Y=0.232$ (solid) / 0.251 (dashed), $X_D = 4 \cdot 10^{-5}$, $\alpha = 1.20$ (sets with different Y are used to enable comparison with other metallicities, and to show that different Y has relatively small effect); **c)** $Z=0.003$, $Y=0.236$, $X_D = 4 \cdot 10^{-5}$, $\alpha = 1.20$.

Table 6. Absolute parameters of the TY CrA eclipsing pair. The second column corresponds to solution #1 from the analysis of *BVRJH*LCs. The third column shows solution #2 resulting from analysis of *BVRJ*LCs only. The mass ratio, q and $K_1 + K_2$ were adopted from the circular solution of Casey et al. (1995). All results are compared with values published by Casey et al. (1998). The larger masses for solution 2 result from lower inclination angle, $i = 82.9^\circ$.

Param.	Solut. 1 [<i>BVRJH</i>]	Solut. 2 [<i>BVRJ</i>]	Casey et al. (1998)
M_1/M_{\odot}	3.11(7)	3.15(7)	3.16(2)
M_2/M_{\odot}	1.61(2)	1.63(2)	1.64(1)
R_1/R_{\odot}	1.46(15)	1.53(13)	1.80(10)
R_2/R_{\odot}	2.30(14)	2.21(12)	2.08(14)
T_1 [K]	12000(500)	12000(500)	12000(500)
T_2 [K]	4894(250)	4977(450)	4900(400)
L_1/L_{\odot}	40(10)	44(10)	67(12)
L_2/L_{\odot}	2.7(7)	2.7(10)	2.4(8)
$\log g_1$ [cgs]	4.60(8)	4.57(7)	4.43(6)
$\log g_2$ [cgs]	3.92(5)	3.96(4)	4.02(5)
a [R_{\odot}]	14.29(9)	14.35(9)	14.29(9)

complicated since the very same tracks and isochrones are not available to us. Therefore, the two mass tracks closest to the measured masses are shown for each component of TY CrA. In addition, models for different deuterium abundances are shown in order to be able to compare with Figs. 8b and 8c. However, the effect of deuterium abundance is small compared to the variations due to age, mass, and metallicity. Obviously, the tracks and isochrones are at variance with the new primary data. An isochrone of older age might still be consistent with the primary, but would disagree with the secondary. Furthermore, the discrepancy with the primary in the mass-radius diagram (Fig. 7a) would not be improved.

In contrast to the mass-radius diagram, the overall situation in the HR diagram does not improve when choosing low-metallicity models. At least, choices of low metallicity allow for agreement of the primary with isochrones of 3 Myr (Fig. 8b)¹¹ and 5 Myr (Fig. 8c), respectively. The disagreement with the mass tracks, however, is exacerbated. Moreover, the low-metallicity tracks disagree with the secondary in the HR diagram. For $Z=0.003$ (Fig. 8c), the evolutionary tracks agree at best marginally with the new secondary parameters. Moreover, no isochrone can be found which matches both components. In summary, low metallicity does not explain the small primary radius, even though this is suggested by the mass-radius diagram.

It is interesting to note, that the models of $Z=0.0125$ might agree with the observations in the HR diagram when adopting a different value of the primary effective temperature which is an input parameter in the LC analysis. While there is no significant effect on the radius measurements, the luminosities derived vary substantially. Nevertheless, the discrepancies in the mass-radius diagram will persist.

¹¹ In Fig. 8b, models for two different helium abundances are shown to allow for a better comparison with Figs. 8a and 8c. Again, the effect is comparably small, in a way similar to the effect of varying deuterium abundance.

6 SUMMARY

We present new optical and NIR photometry of TY CrA taken in 2006-2011. The *BVRI* photometry taken complements the Strömgren photometry studied by Casey et al. (1998). For the first time, we present NIR light curves of the secondary minimum taken in the *J* and *H* bands. In contrast to the optical light curves the secondary minimum is much better revealed in the NIR and is more than 0.1 mag deep

We compiled all minima times available to us so that the O-C diagram of TY CrA now spans over two decades. The light-time effect of the spectroscopic tertiary is too small to explain the changes in the O-C diagram. There are probably other effects complicating the analysis like shifts of the observed minima due to photometric out-of-eclipse variability. We find, that RV measurements are more suitable to solve the tertiary orbit. One requires high-resolution high S/N spectroscopy with an echelle spectrograph at a 2-m class telescope covering at least one orbital period of the unresolved triple system (270 days most probably). The Fourier-domain technique (see Hadrava 1995) then can be used to disentangle the component's spectra for further analysis (T_{eff} , $\log g$, $\log [M/X]$) and to improve the spectroscopic orbits. The orientation of the components' rotational axes could be found analyzing the McLaughlin rotational effect during eclipses of the inner pair. Long-baseline interferometry would help to determine orbital parameters of the outer orbit of the triple and to determine the distance to the system (comparing interferometric and spectroscopic semi-major axis of the inner triple system) and the total mass of the triple.

For the first time, we present a multi-band solution of the light curve of the inner eclipsing binary in both optical and near-*IR* bands. The near-*IR* data requires to account for a third light contribution and thus also allows us to constrain the colours of the third light. The third light is composed of at least three sources which are the reflection nebula, the spectroscopic tertiary, and the visual fourth component.

Only the radius and the luminosity of the primary do not agree with the values published by Casey et al. (1998). Agreement is not improved by restricting the analysis to the optical data. While the primary luminosities could be reconciled by adjusting the effective temperature of the primary, the derived primary radius is very robust and would not change.

Indeed, the absolute parameters of TY CrA do not agree with expectations. The primary component seems undersized when compared to other stars of same mass and to recent PISA evolutionary tracks and isochrones. The HR diagram shows that low metallicity cannot explain the small radius of the primary. As speculated by Casey et al. (1998), the subsynchronous rotation of the primary and effects on its internal structure might play a role.

A very interesting question is whether the fourth component is actually bound to the TY CrA system. In order to decide whether the fourth component is bound, there is need for single-epoch AO observation of the system to establish the physical bond of the fourth visual component 0".3 away in 2002. If it was a background star, the proper motion of TY CrA (see Table 1) would make the visual companion

unresolved around 2012. Because of the high total mass of the whole system the orbital period of the outermost visual orbit is probably rather short: assuming a distance of $d = 130$ pc, the 0".294 separation observed in 2002 as the semi-major axis and the total mass of the system as $7 M_{\odot}$, we get $P_{1234} = 89.3$ years.

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